

Advanced Teleoperation, Graphics Aids, and Application to Time Delay Environments

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ABSTRACT

Advanced graphics interfaces for space telerobotics applications are illustrated by examples developed at the JPL Advanced Teleoperation Laboratory. Application examples include task analysis and planning displays for a teleoperated Solar Maximum Satellite repair task, a novel force-reflecting teleoperationsimulator for operator training, and preview/predictive displays with calibrated graphics overlay for on-line remote servicing operations, for example, ground remote control of space robots with time delay.

I. INTRODUCTION

Advances in computer graphics technologies enable the design, development, and use of high-fidelity graphics displays for very efficient operational aid in space telerobotics. Advanced graphics techniques [6] can be used to achieve increased reliability in all three phases of space telerobotic operations: in off-line task analysis and planning, in operator training, and in on-line task execution. This paper addresses potential use of graphics displays in all three phases of space telerobotics flight operations.

In particular, on-line preview/predictive displays for ground-controlled telerobotic servicing, in space will be described in detail. In the new "previewed" predictive display strategy for enhanced operational safety, the operator interacts with the graphically simulated "virtual environment" first before sending the robot arm motion command to the remote site for actual execution. In order to accurately match graphically simulated "virtual environment" with the real task environment, operator-interactive reliable camera calibration and object localization algorithms are used.

II. TASK ANALYSIS AND PLANNING DISPLAYS

Graphics displays can provide substantial aid in off-line task analysis and planning, for example, to investigate workcell layout, motion planning with collision detection and with possible redundancy resolution, planning for camera images, and continuous motion

simulation. Graphics displays are used for task analysis and planning of Solar Maximum Satellite Repair (SMSR) task. The Solar Maximum Repair Mission [?] was successfully completed by two astronauts through a 7-hour extra vehicular activity (EVA) in 1984. In this mission, the Solar Maximum Mission (SMM) satellite was captured and berthed in the Space Shuttle cargo bay by using the Shuttle Remote Manipulator System (RMS), and then three tasks were performed prior to the deployment of the repaired satellite. The most difficult task among the three was the Main Electronics Box (MEB) repair. The teleoperated MEB repair task has been partially demonstrated in the Advanced Teleoperation Laboratory (ATOP) by using a dual-arm force-reflecting teleoperation system equipped with recent advanced control and graphics display techniques.

The workcell of the simulated SMSR task (Fig. 1) consists of two 8-dof AAI robot arms, a partial SMM satellite mockup, two "smart" hands (end effectors), a raised tile floor. Other workcell elements include camera gantry frame and various end effector tools such as a power-driven screw driver, a tape cutter, and a diagonal cutting plier. In order to determine the desirable

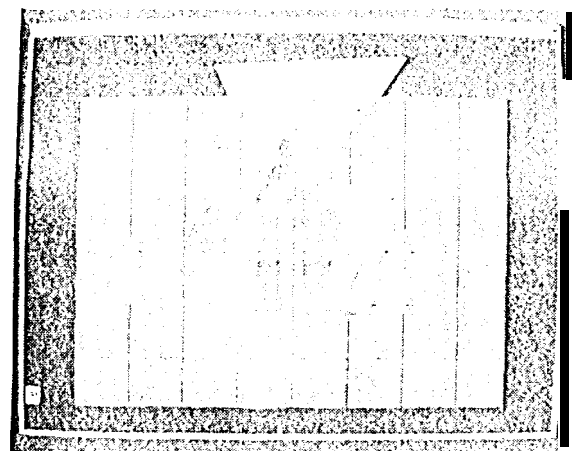


Fig. 1. Graphics display of the simulated Solar Maximum Satellite Repair (SMSR) setup with an overlay of the reach envelope of the right robot hand for task analysis and planning.

mounting locations of the robots and the satellite mockup, reach envelopes of robots were overlaid on the workcell display graphics for various task conditions, where each device was allowed to be moved to satisfy the reach envelope constraints. An example of the reach envelope analysis is shown in Fig. 1 to determine the opening angle of the MEB panel. When the panel is 100° opened, some of the connector screws near the hinge assembly cannot be reached by the screw driver at the right angle. Further careful reach envelope analysis indicates that when the panel is 115° opened, the screw driver can reach all the connector screws at the right angle to the panel as shown in Fig. 1.

Other task analysis and planning examples include motion planning with collision detection, redundancy management, planning for camera views, and complete motion simulation using graphics displays. A final verified planned task sequence and the motion simulation for each task segment can be used later for preview display during the on-line task execution.

III. OPERATOR TRAINING DISPLAYS

Graphics displays can also serve as an introductory training tool for operators. Teleoperation in general demands considerable training, and robots can be damaged during the initial stages of the training. Prior to training with actual robots, a telerobot simulator can be used during the initial training. Introductory training with a simulator can save time and cost for space crew training.

Recently we have developed a force-reflecting teleoperation simulator/trainer [5], [8] as a possible computer-aided teleoperation training system (Fig. 2). A novel feature of this simulator is that the operator actually feels virtual contact forces and torques of a compliantly controlled robot hand through a force reflecting hand controller during the execution of the simulated peg-in-hole task. The simulator allows the user to specify force reflection gains and the stiffness (compliance) values of the manipulator hand for both the three translational and the three rotational axes in Cartesian space. The location of the compliance center can also be specified, although initially it is assumed to be at the grasp center of the manipulator hand.

A peg-in-hole task is used in our simulated teleoperation trainer as a generic teleoperation task. An in-depth quasi-static analysis of a two-dimensional peg-in-hole task has been reported earlier [12], but the two-dimensional model is not sufficient to be utilized in a teleoperation trainer. This two dimensional analysis is thus extended to a three-dimensional peg-in-hole task, so that the analysis can be used in our simulated teleoperation trainer. In order to have finite contact forces and torques, both lateral and angular compliance must be provided for the system. In our simulation, the hole and its support structure are assumed to be rigid with

infinite stiffness, while the robot hand holding the peg is compliant for all cartesian translational and rotational axes (Fig. 3). We further assume that the compliance center is located at a distance l from the tip of the peg with three lateral springs and three angular springs. Detailed computational procedures can be found in [5], [8]. A more generalized method of computing contact forces and torques based on a general collision detection algorithm is under consideration.

A high fidelity real time graphics simulation of the peg-in-hole task with a PUMA arm and a generic task board has been accomplished by using a Silicon Graphics II(486)/310 VGX workstation, which is very fast both in computation and in graphics rendering with hardware-supported hidden surface removal and lighting. When force/torque computations are involved due to contact, the update rate is about 16 frames/s. The 6-dof hand controller motion commanded by the human

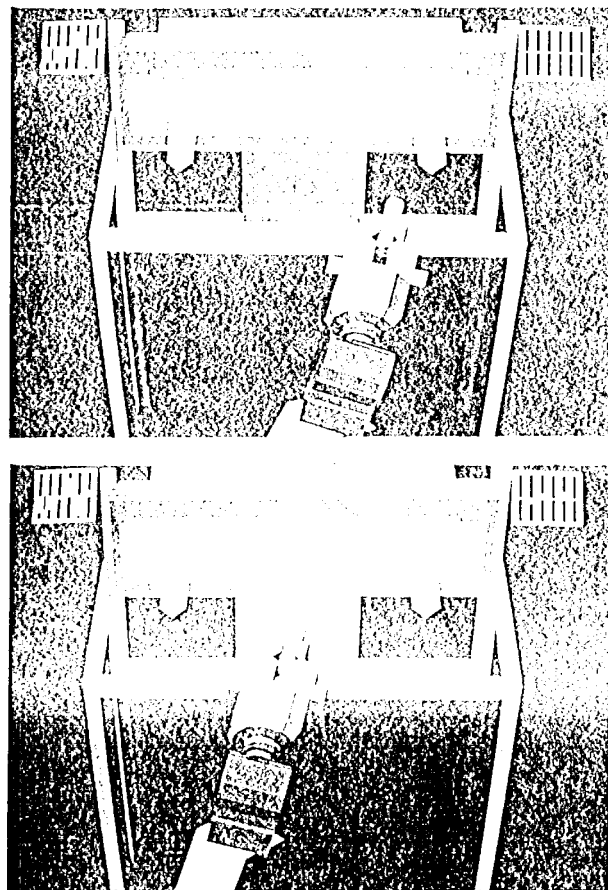


Fig. 2. Force-reflecting teleoperation training displays before contact (upper) and during insertion (lower). Contact forces and torques are computed and reflected to the force reflecting hand controller in real-time. They are also displayed on the upper left corner of the screen, while the current joint angles appear on the upper right corner.

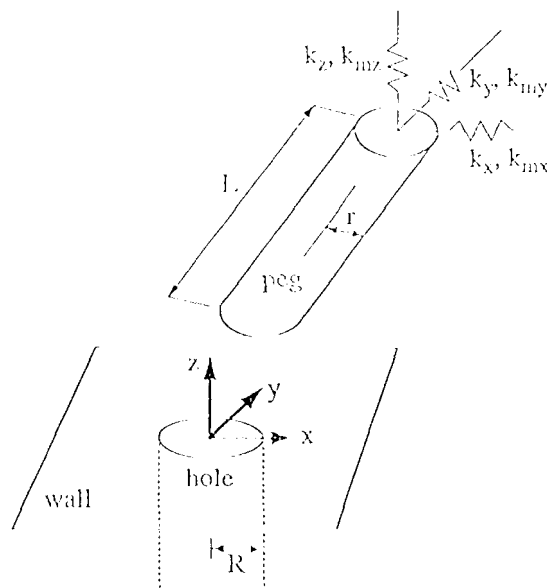


Fig.3. Geometry of a simulated peg-in-hole task with lateral and angular springs at the compliance center.

operator is sent to the graphics simulation display through a serial I/O line at an about 30 Hz data update rate. Virtual contact forces and torques are computed in real time and fed back to the hand controller through the serial I/O line at an about 30 Hz data update rate.

Testings with the developed peg-in-hole task simulator/trainer indicate that appropriate compliance values are essential to achieve stable force-reflecting teleoperation in performing the simulated peg-in-hole task. As the compliance values of the simulated robot hand becomes smaller, the operator must hold the force-reflecting hand controller more firmly to maintain the stability of teleoperation.

IV. ON-LINE PREVIEW/PREDICTIVE DISPLAYS

Graphics displays can also provide effective operator aid during the on-line operation. In particular, we have recently developed on-line graphics aids for ground-controlled telerobotic servicing in space, which has potential operational benefits in future space missions. Possible future applications include ground-controlled telepresence experiments, ground-controlled remote maintenance/repair of spacecrafts including Space Station Freedom, and ground-controlled remote assembly/construction work on the Moon or Mars. An imminent potential application includes ground-controlled telerobotic servicing of the Hubble Space Telescope (HST) to assist EVA (Extra Vehicular Activity; space walk) astronauts performing a maintenance mission in the Space Shuttle cargo bay. In a conceivable telerobot-assisted EVA maintenance scenario, EVA astronauts will capture and berth the HST on the Shuttle bay and perform critical tasks, while some other

tasks such as open/close HST tool box, deploy/stow crew aids, and replace ORU's can be potentially carried out by telerobotic operations from the ground. This telerobotic assistance is expected to reduce astronauts' EVA time, and thus save operational cost.

In such ground-controlled remote operations, however, there is an unavoidable communication time delay. The round-trip time delay of the communication link between the ground station and a space telerobot in low Earth orbit is expected to be 2 to 8 seconds to relay data via several communication satellites and ground stations. It is in general difficult for the human operator to control a remote manipulator when the communication time delay exceeds 1 second. The best known strategy to cope with time delay is the "move and wait" strategy [3]. In this strategy, the operator moves the manipulator a small distance and then waits to see what happens before the next move. Two important schemes that enhance telemanipulation task performance under communication time delay are shared compliance control and predictive display [1], [6]. A recent report [7] based on peg-in-hole experiments under 0 to 4 s time delays indicated that the use of compliance/impedance control in the remote site is essential and promising for time-delayed teleoperation.

In a predictive display, the graphics model responds immediately to the human operator's hand controller commands, while the actual camera view of the arm responds with a communication time delay. Thus the predictive display provides the operator with the non-time-delayed or predicted motion of the robot arm. A predictive display system was originally developed earlier by using a stick figure model of the robot arm overlaid on the actual video image of the arm [11]. We have extended stick-figure-type predictive display technology to high-fidelity 3-D predictive display technology for applications to ground-controlled telerobotic servicing in space with communication time delay. High fidelity is achieved by 1) precise 3-D graphics modeling/rendering, 2) operator-interactive reliable camera calibration and object localization that enable accurate calibrated overlay of graphics models on the live video of quasi-static telerobotic task environments, and 3) use of the same control software to drive the local-site simulated robot which drives the remote-site real robot.

Although various camera calibration and object localization algorithms have been reported, we recently developed a methodology of using general-purpose operator-interactive camera calibration and object localization algorithms to achieve reliable, high fidelity calibrated graphics overlay. The developed algorithms also provide a key technology of matching simulated graphics "virtual environment" with the real task environment reliably and accurately based on visual sensor data of video camera views, enabling interactive graphics-

model-based control incorporated with operator-assisted sensor-based control as an approach to efficient telerobotic servicing in general regardless of time delay. Examples of calibrated graphics overlay after camera calibration and object localization are shown in Fig. 4.

Predictive displays with calibrated graphics overlay have been further extended to "previewed" predictive displays. In the original "real-time" predictive display, the operator-commanded hand controller motion drives both the simulated graphics model (without delay) and the real robot arm (with communication time delay) simultaneously. In this "previewed" predictive display, the operator first interacts with the graphically simulated "virtual environment" by driving the simulated graphics model to perform a desired segment of the task. The operator then sends the motion command to the remote site for actual motion execution, only after verifying the commanded motion through graphics

preview. This "previewed" predictive display operation is repeated for each new task segment.

A typical scenario to perform a task segment with "previewed" predictive displays would be as follows. 1) The operator drives the simulated robot arm with a hand controller by using preview/predictive graphics displays and records the robot motion trajectory. 2) The operator plays back the recorded robot motion with an appropriate time scale by again driving the simulated arm to preview and verify the robot motion trajectory. This preview verification is important to ensure operational safety. 3) The operator sends the verified trajectory to the remote site, and the remote system stores the trajectory data in a buffer. This trajectory data buffering ensures accurate motion execution even with slow or abrupt change in the communication time delay. 4) After the receipt of the whole trajectory, the remote system executes the robot motion trajectory command to drive the actual robot arm. During the execution, compliance/impedance control can be activated. In the local site, the operator monitors the command execution by visually observing the preview/predictive display updated with the returned video image of the robot arm motion. 5) After the completion of the robot motion execution, the graphics model of the arm is updated with the actual final robot joint angles. This updated procedure not only eliminates accumulation of motion execution errors but also enables the preview/predictive display to be useful even when the compliance/impedance control is activated in the remote site, for example, during the performance of a contact or insertion task.

Operator interface is an important element for efficient interactions between the human operator and the telerobotic system. Advances in graphics and graphical operator interface (GUI) technologies enable development of very efficient graphical operator interfaces [4]. A graphical operator interface that supports the "previewed" predictive display strategy has been developed. Two Silicon Graphics workstations and one NTSC video monitor are currently used. The primary workstation (IRIS-4D/310 VGX) is used for the live video picture and for various GUI's. A Silicon Graphics Videolab board installed in the primary workstation captures the live video picture at 30 frames/s, and supports real-time graphics overlay to appear together on the high-resolution (1280×1024) workstation monitor and the low-resolution video monitor simultaneously. The second workstation (IRIS-4D/70 GT) is solely used for sensor data display providing graphical visualization of robot arm joint angles, 6-dof force/torque sensor data, and capacitive proximity sensor data.

A top-level screen layout on the primary workstation is shown in Fig. 5. It consists of two NTSC-



Fig. 4. Calibrated overlays of both the robot arm and the ORU graphics models on the live video picture after the camera calibration and object localization for four calibrated camera views. oblique-view camera (upper) and overhead camera with zoom in (lower).

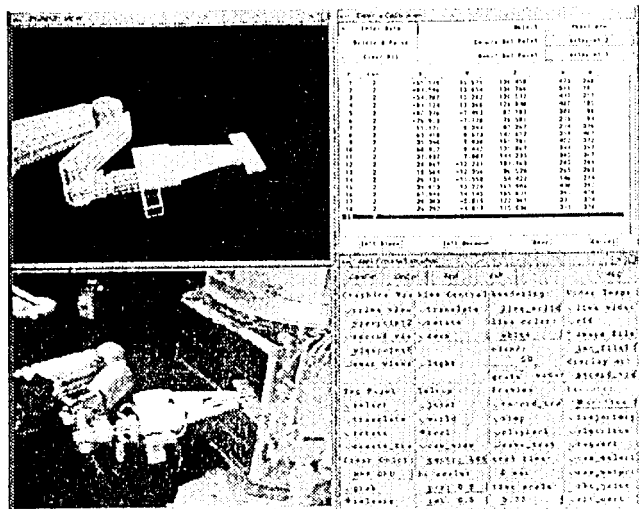


Fig. 5. Top-level graphical operator interface.

resolution (646x486) windows on the left side and two slightly smaller windows on the right side. During the camera calibration and object localization, a 3-D graphics display appears on the upper left window, live video picture on the lower left window, camera calibration or object localization GUI on the upper right window, and graphics/robot control main GUI on the lower right window. During the actual teleoperation after the camera calibration and object localization, a calibrated graphics overlay on the live video picture appears on the upper left window, 3-D graphics display of either a calibrated view that matches with a real camera view or an operator-defined virtual camera view (of any desired viewing position and angle) on the lower left window, another 3-D graphics display or task auto sequencing GUI on the upper right window, and graphics/robot control main GUI on the lower right window.

V. ORU Changeout Remote Servicing Demonstration

The developed "previewed" predictive displays have been successfully utilized in demonstrating a ground-simulated ORU changeout remote servicing task by remotely operating a robot arm at NASA Goddard Space Flight Center from the Jet Propulsion Laboratory. The demonstration is to show potential capabilities of ground-controlled telerobotic servicing. The Engineering Test Bed Robotics Lab at NASA Goddard Space Flight Center has an Explorer Platform (EP) spacecraft mockup with an h4MS (Multi-Mission Servicing) ORU module. The EP spacecraft, which was launched in 1992, is a modular mission spacecraft, carrying several modules that can be replaced on orbit by astronauts. In the demonstration a Robotics Research Corporation K-1607 robot arm and a Lightweight Servicing Tool (LST; socket driver power tool) mounted at the end of the arm were used [10].

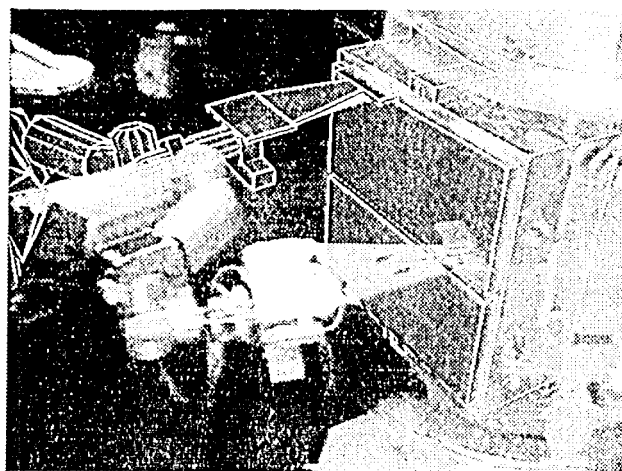


Fig. 6. An example of preview/predictive displays with calibrated graphics overlay during the performance of the JPL-Goddard remote servicing demonstration of an ORU changeout task.

For live video image transmission from NASA-GSFC to JPL, the NASA Select NTSC Television broadcasting channel is used (30 frames/s; the delay may be about 0.5 s). For a bidirectional command/data link, TCP/IP socket communication with ethernet connection through the Internet computer network is used. The round-trip Internet socket communication delay between JPL and NASA-GSFC was measured about 0.1 s on the average, although there were often long time delays (e.g., a 10-minute testing indicated that about 0.8% of the delays was longer than 0.5 s and about 0.01 % was longer than 4 s). A telephone line is also provided for voice communication during the demonstration.

Examples of calibrated graphics overlays for 2 different camera views are shown in Fig. 4. The average camera calibration and object localization errors on the image plane were less than 2% for all four camera views. An example of preview/predictive displays with calibrated graphics overlay during the performance of the remote ORU changeout task is shown in Fig. 6.

VI. CONCLUSION

New developments and applications of graphics displays in all three phases of off-line task analysis/planning, simulated training, and on-line task execution to reduce operation uncertainties and increase operation efficiency and safety were described. Task analysis/planning displays provided substantial aid in investigating workcell layout, robot motion planning, and sensor planning for a simulated SMSR task. A force-reflecting training simulator with visual and kinesthetic force virtual reality was developed to serve as an introductory training tool prior to training with

actual robots. Finally, on-line high-fidelity 3-D preview/predictive displays were described for applications to ground-controlled telerobotic servicing in space. Simulated graphics "virtual environment" was matched with the remote site real task environment by using operator-interactive camera calibration and object localization methods. In the "previewed" predictive display strategy for enhanced operational safety, the operator interacts with the graphically simulated virtual environment first, and only after graphics preview verification, the operator sends the motion execution command to the remote site.

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